

Time-dependent CP asymmetry in $B^0 \rightarrow \rho^0 \gamma$ decay to probe the origin of CP violation

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Since the CP violation in the B system has been investigated up to now only through processes related to the B - \bar{B} mixing, urgently required is new way of study for the CP violation and establishing its origin in the B system independent of the mixing process. In this work, we explore the exclusive $B^0 \rightarrow \rho^0 \gamma$ decay to obtain the time-dependent CP asymmetry in $b \rightarrow d$ decay process in the standard model and the supersymmetric model. We find that the complex RL and RR mass insertion to the squark sector in the MSSM can lead to a large CP asymmetry in $b \rightarrow d \gamma$ decay through the gluino-squark diagrams, which is not predicted in the Standard Model induced by the B - \bar{B} mixing.

I. INTRODUCTION

The unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix yields the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which describes a triangle on the complex plane. The angles of this triangle are defined by

$$\alpha(\phi_2) \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta(\phi_1) \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma(\phi_3) \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right), \quad (1)$$

of which non-zero values indicate the existence of the CP violation. In the B meson system, the CP asymmetry in $B \rightarrow J/\psi K_S$ decays, which is directly related to $\sin 2\beta$ through B^0 - \bar{B}^0 mixing, has been measured and agrees well with the standard model (SM) prediction by the CKM unitarity. Since the present CP violating asymmetry appears via β , presently measured only through processes involving the B^0 - \bar{B}^0 mixing, it is strongly required to find new observables of the CP violation in the B system and establish that the measured β indeed originates from V_{td} of the CKM in a way independent of the mixing. Within the SM the source of the CP violation of the B system (and the weak phase β) is nothing but the phase of CKM matrix element V_{td} in the leading order. The magnitude and the phase of V_{td} cannot be measured in a direct manner due to top quark's fast decay before its hadronization. This leaves only indirect methods for experimental determination in various processes.

As is well known, $\sin 2\beta$ can be determined independently of the B^0 - \bar{B}^0 mixing in a theoretically clean manner, up to $\Delta \sin 2\beta \approx \pm 0.10$, provided $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $B(K_L \rightarrow \pi^0 \nu \bar{\nu})$ are measured within $\pm 10\%$ accuracy [1]. Why do we urgently require yet another method to examine the CP violation in the B system? The main reason is that this area is very likely to yield information about new physics beyond the SM. We expect that new physics can influence the $\Delta B = 1$ penguin decays in a different way than the usual $\Delta B = 2$ mixing. Examples are the *possibly* large new physics effects recently measured in $b \rightarrow s \bar{s} s$ decays. The measurements of $\sin 2\beta$ in $b \rightarrow s \bar{s}$ decays may have shown deviations from that in $B \rightarrow J/\psi K_S$ decay, which are still controversial [2]. A sizable difference between them could be a clear evidence of the new physics beyond the SM. If one of such discrepancy indeed exists, it implies an evidence of a new physics effect beyond the SM [3], and also suggests an interesting possibility that the new physics effect is large in the penguin diagrams while its contribution to the B^0 - \bar{B}^0 mixing is small.

The Cabibbo-suppressed $b \rightarrow d \gamma$ decay also involves V_{td} and provides us a new chance to measure the weak phase β in a way independent from the mixing to study the CP violation in the B system. Although the inclusive $B \rightarrow X_d \gamma$ decay is a theoretically clean process to determine V_{td} [4], it can be hardly discriminated from large $B \rightarrow X_s \gamma$ background in the experiment. Thus our interest is devoted to the study of the exclusive channels, $B \rightarrow \rho \gamma$ and $B \rightarrow \omega \gamma$. The first measurement on the branching ratio of $b \rightarrow d \gamma$ process,

$$\text{Br}(B \rightarrow \rho/\omega \gamma) = (1.8_{-0.5}^{+0.6} \pm 0.1) \times 10^{-6},$$

has been reported at the Moriond conference [5]. Implications of $B \rightarrow \rho \gamma$ and $B \rightarrow \omega \gamma$ decays in the SM and the MSSM have been studied in the literature [6, 7, 8]. The charged $B^\pm \rightarrow \rho^\pm \gamma$ decay mode provides clean signal and has a branching ratio twice larger than that of the neutral mode, by the isospin symmetry. However, the long-distance (LD) effect on the charged mode due to dominantly W^\pm -annihilation is very large ($\sim 30\%$), which contaminates the CP violating effect [9, 10]. Consequently here we study the $B^0 \rightarrow \rho^0 \gamma$ decay to explore the CP violation. The time-dependent CP asymmetry in the neutral $B^0 \rightarrow \rho^0 \gamma$ decay probes the CP violation in the interference between decay

and mixing as well as the direct CP violation, and it leads to the extraction of β from both decay and mixing. We note that the photon has two helicity states γ_L and γ_R which cannot be discriminated in the B factory experiments. Since CP violating asymmetry is defined when both B and \bar{B} mesons decay into a same state, what we actually measure is the CP asymmetries with the definite helicity in the final states. In the SM, the operator which governs $b \rightarrow d\gamma$ decay is chiral and the term with the conjugate operator is suppressed by m_d/m_b and the CP asymmetry also suppressed accordingly. Therefore, the new physics beyond the SM which involves a sizable right-handed operator is required for a large time-dependent CP asymmetry enough being observed in the experiment [11].

In this letter, we consider the supersymmetric models which have non-diagonal elements of the squark mass matrices in the so-called super-CKM basis as a new physics model. The non-diagonality of the down-type squark mass matrix is parameterized by the mass insertions

$$(\delta_{ij})_{MN} \equiv (\tilde{m}_{ij}^2)_{MN}/\tilde{m}^2,$$

where \tilde{m} is the averaged squark mass. Here i and j are flavor indices and M and N denote chiralities, L or R . The δ 's are complex in general and provide new CP phases. To clarify and simplify our discussion, we consider the $(\delta_{13})_{RL}$ and $(\delta_{13})_{RR}$ dominating cases to produce the right-handed operators in the present work. We note that the $(\delta_{13})_{LR}$ and $(\delta_{13})_{LL}$ mass insertions leads to the left-handed operators and cannot generate the CP asymmetry only by themselves. The $\Delta B = 1$ decay amplitude depends on $(\delta_{13})_{RL,RR}$ linearly, while the dependence of M_{12} for the $\Delta B = 2$ process is quadratic. Then $b \rightarrow d\gamma$ decay would be more sensitive to the SUSY contribution than the $B - \bar{B}$ mixing process when the SUSY effects are smaller than the SM values as usual. Thus we can observe the new physics effect through decay process which is not observed through mixing induced processes. In section II, we describe the $B^0 \rightarrow \rho^0\gamma$ decay and the time-dependent CP asymmetry. The supersymmetric contributions are given in section III and the numerical results given in the section IV. We conclude in section V.

II. CP ASYMMETRY IN $B^0 \rightarrow \rho^0\gamma$ DECAY

The relevant terms of the effective Hamiltonian for the $b \rightarrow d\gamma$ decay is written as

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & \frac{4G_F}{\sqrt{2}} \sum_{q=u,c} [V_{qb}V_{qd}^* (C_1 O_1^q + C_2 O_2^q + C_1' O_1'^q + C_2' O_2'^q), \\ & -V_{tb}V_{td}^* (C_7^{\text{eff}} O_7 + C_7'^{\text{eff}} O_7') + \dots], \end{aligned} \quad (2)$$

where the operators are given by

$$\begin{aligned} O_1^q &= (\bar{d}_L^\alpha \gamma_\mu q_L^\beta)(\bar{q}_L^\beta \gamma^\mu b_L^\alpha), \\ O_2^q &= (\bar{d}_L \gamma_\mu q_L)(\bar{q}_L \gamma^\mu b_L), \\ O_7 &= (em_b/16\pi^2)\bar{d}_L \sigma_{\mu\nu} F^{\mu\nu} b_R, \end{aligned} \quad (3)$$

and O_i' are their complex conjugate operators. The effective Wilson coefficient $C_7^{(\prime)\text{eff}}$ includes the effects of operator mixing.

In the SM, C_7^{eff} is suppressed by the mass ratio m_d/m_b and so is the right polarized photon emission $b_L \rightarrow q_R \gamma_R$. The photon emission with the momentum q and the polarization vector $\epsilon_\mu(q)$ yields the electromagnetic field strength $F_{\mu\nu} = i(\epsilon_\nu q_\mu - \epsilon_\mu q_\nu)$. The hadronic matrix element of $B \rightarrow \rho\gamma$ process is parameterized in terms of two invariant form factors F_1^s and F_2^s and the polarization vector of the ρ meson, $\epsilon_\mu(k)$. We can set $F_1^s = F_2^s \equiv F^s$ at $q^2 \sim 0$ for the real photon emission [12]. We write the amplitudes for the final states of polarized photon as

$$\begin{aligned} A_L &\equiv \langle \rho\gamma_L | H_{\text{eff}} | B^0 \rangle = \frac{4G_F}{\sqrt{2}} C_7^{\text{eff}*} V_{tb}^* V_{td} \langle \rho\gamma_L | O_7'^{\dagger} | B^0 \rangle, \\ A_R &\equiv \langle \rho\gamma_R | H_{\text{eff}} | B^0 \rangle = \frac{4G_F}{\sqrt{2}} C_7^{\text{eff}*} V_{tb}^* V_{td} \langle \rho\gamma_R | O_7'^{\dagger} | B^0 \rangle, \\ \bar{A}_L &\equiv \langle \rho\gamma_L | H_{\text{eff}} | \bar{B}^0 \rangle = \frac{4G_F}{\sqrt{2}} C_7^{\text{eff}} V_{tb} V_{td}^* \langle \rho\gamma_L | O_7 | \bar{B}^0 \rangle, \\ \bar{A}_R &\equiv \langle \rho\gamma_R | H_{\text{eff}} | \bar{B}^0 \rangle = \frac{4G_F}{\sqrt{2}} C_7^{\text{eff}} V_{tb} V_{td}^* \langle \rho\gamma_R | O_7 | \bar{B}^0 \rangle, \end{aligned} \quad (4)$$

where

$$\begin{aligned}
\langle \rho(k) \gamma_L(q) | O_7 | \bar{B}^0(p) \rangle &= \frac{em_b}{16\pi^2} \epsilon^\mu(q) \epsilon^\nu(k) [\epsilon_{\mu\nu\alpha\beta} p^\alpha q^\beta - i(g_{\mu\nu}(q \cdot p) - p_\mu q_\nu)] \cdot 2F^s(q^2 \sim 0), \\
&= \langle \rho \gamma_L | O_7' | B^0 \rangle, \\
\langle \rho(k) \gamma_R(q) | O_7' | \bar{B}^0(p) \rangle &= \frac{em_b}{16\pi^2} \epsilon^\mu(q) \epsilon^\nu(k) [\epsilon_{\mu\nu\alpha\beta} p^\alpha q^\beta + i(g_{\mu\nu}(q \cdot p) - p_\mu q_\nu)] \cdot 2F^s(q^2 \sim 0), \\
&= \langle \rho \gamma_R | O_7^\dagger | B^0 \rangle.
\end{aligned} \tag{5}$$

For the neutral B meson decay, the LD contribution due to W -exchange is merely a few % from the QCD sum rule calculation [9, 10], so it will be ignored in our analysis. We investigate the time-dependent CP asymmetry of neutral B mesons, which probes the direct CP violation and extracts the weak phase in mixing and decay. Since we cannot measure the photon helicity in practice, the asymmetry which we will measure in the experiment is given by

$$\begin{aligned}
A_{\text{CP}}(t) &= \frac{[\Gamma(\bar{B}_{\text{phys}}^0 \rightarrow \bar{\rho}^0 \gamma_L) + \Gamma(\bar{B}_{\text{phys}}^0 \rightarrow \bar{\rho}^0 \gamma_R)] - [\Gamma(B_{\text{phys}}^0 \rightarrow \rho^0 \gamma_L) + \Gamma(B_{\text{phys}}^0 \rightarrow \rho^0 \gamma_R)]}{\Gamma(\bar{B}_{\text{phys}}^0 \rightarrow \bar{\rho}^0 \gamma_L) + \Gamma(\bar{B}_{\text{phys}}^0 \rightarrow \bar{\rho}^0 \gamma_R) + \Gamma(B_{\text{phys}}^0 \rightarrow \rho^0 \gamma_L) + \Gamma(B_{\text{phys}}^0 \rightarrow \rho^0 \gamma_R)} \\
&\equiv -\mathcal{C} \cos(\Delta m_B t) + \mathcal{S} \sin(\Delta m_B t),
\end{aligned} \tag{6}$$

where

$$\mathcal{S} = \frac{|A_L|^2 \text{Im} \lambda_L + |A_R|^2 \text{Im} \lambda_R}{|A_L|^2 + |A_R|^2}, \tag{7}$$

with the parameter $\lambda_{L(R)}$ defined by

$$\lambda_{L(R)} \equiv \sqrt{\frac{M_{12}^*}{M_{12}}} \frac{\bar{A}_{L(R)}}{A_{L(R)}}. \tag{8}$$

Since $|A_L| = |\bar{A}_R|$ and $|A_R| = |\bar{A}_L|$, the coefficient $\mathcal{C} = 0$ identically. The off-diagonal element M_{12} describes the B^0 - \bar{B}^0 mixing and $A_{L(R)}$ is the amplitude for the $b \rightarrow d \gamma_{L(R)}$ decays. We define

$$\begin{aligned}
\beta_{\text{mix}} &= \frac{1}{2} \text{Arg}(M_{12}), \\
\beta_{\text{decay}} &= \frac{1}{2} \text{Arg}\left(\frac{\bar{A}_R}{A_R}\right) = \frac{1}{2} \text{Arg}\left(\frac{\bar{A}_L}{A_L}\right),
\end{aligned} \tag{9}$$

and the coefficient \mathcal{S} is expressed by

$$\mathcal{S} = -\frac{2 |C_7| |C_7'|}{|C_7|^2 + |C_7'|^2} \sin(2\beta_{\text{mix}} - 2\beta_{\text{decay}}). \tag{10}$$

We can write

$$2\beta_{\text{decay}} = 2\beta_{\text{SM}} + \text{Arg}(C_7') + \text{Arg}(C_7). \tag{11}$$

Note that we have an additional factor $2 |C_7| |C_7'| / (|C_7|^2 + |C_7'|^2)$, which can enhance or suppress \mathcal{S} by the new physics effect $|C_7'|$. In the SM, $|C_7'|/|C_7| \sim \mathcal{O}(m_d/m_b)$ and the CP asymmetry is also suppressed by the corresponding factor.

III. SUSY CONTRIBUTIONS

We consider the gluino mediated penguin diagram contribution to $b \rightarrow d \gamma$ decay in the MSSM. By penguin diagrams with gluino-squark loop, the Wilson coefficients C_i' in the effective Hamiltonian of Eq. (2) get contribution to produce γ_R at the matching scale $\mu = m_W$. After the RG evolution, we have

$$\begin{aligned}
C_7^{\text{eff}}(m_b) &= -0.31, \\
C_7'^{\text{eff}}(m_b) &= \frac{\sqrt{2}}{G_F V_{tb} V_{td}^*} (0.67 C_7^{\text{SUSY}}(m_W) + 0.09 C_8^{\text{SUSY}}(m_W)),
\end{aligned} \tag{12}$$

where the SUSY contributions are

$$\begin{aligned} C_7^{\text{SUSY}}(m_W) &= \frac{4\alpha_s\pi Q_b}{3\tilde{m}^2} \left[(\delta_{13})_{RR} M_4(x) - (\delta_{13})_{RL} 4B_1(x) \frac{m_{\tilde{g}}}{m_b} \right], \\ C_8^{\text{SUSY}}(m_W) &= \frac{\alpha_s\pi}{6\tilde{m}^2} \left[(\delta_{13})_{RR} (9M_3(x) - M_4(x)) + (\delta_{13})_{RL} \left(4B_1(x) - 9\frac{B_2(x)}{x} \right) \frac{m_{\tilde{g}}}{m_b} \right], \end{aligned} \quad (13)$$

with the squark mass insertions $(\delta_{13})_{RL}$ and $(\delta_{13})_{RR}$ and the squared mass ratio of the gluino mass to the average squark mass $x = (m_{\tilde{g}}/\tilde{m})^2$ [13, 14, 15]. Note that the SUSY contribution is more sensitive to $(\delta_{13})_{RL}$ than $(\delta_{13})_{RR}$ due to the enhancement factor $m_{\tilde{g}}/m_b$. The loop functions $B_i(x)$ are found in the literature [13, 14, 15]. Since $\delta_{RL,RR}$ are complex in general, the Wilson coefficients $C_7^{\text{eff}}(m_b)$ has nontrivial phase which affects the phase of \bar{A}/A .

On the other hand, the B - \bar{B} mixing is affected by the gluino-squark box diagrams in the MSSM. Unlike the $\Delta B = 1$ case, the relevant $\Delta B = 2$ effective Hamiltonian with the supersymmetric contribution contains new operators which consist of scalar-scalar interactions,

$$\begin{aligned} O'_{S2} &= (\bar{d}_\alpha(1+\gamma_5)b_\alpha)(\bar{d}_\beta(1+\gamma_5)b_\beta), \\ O'_{S3} &= (\bar{d}_\alpha(1+\gamma_5)b_\beta)(\bar{d}_\alpha(1+\gamma_5)b_\beta), \end{aligned} \quad (14)$$

when we introduce only the RL and RR mass insertions. The Wilson coefficients $C_{1,S2,S3}$ corresponding to the SM operators $O_1 = (\bar{d}\gamma_\mu(1-\gamma_5)b)(\bar{d}\gamma_\mu(1-\gamma_5)b)$ and $O_{S2,S3} = O'_{S2,S3}(L \leftrightarrow R)$ consist of the SM part and the supersymmetric contributions, while C'_{S2} and C'_{S3} corresponding to the above operators are entirely supersymmetric. Their explicit expression at the scale $\mu = M_{\text{SUSY}}$ can be found in Refs. [16, 17]. Ignoring the RG running effects between M_{SUSY} and m_W , we perform the RG evolution from m_W to m_b scale to obtain the evolved Wilson coefficients. The SUSY contributions are given by

$$C^{(r)}_i^{\text{SUSY}}(m_b) = \sum_k \sum_j \left(b_k^{(i,j)} + \eta c_k^{(i,j)} \right) \eta^{a_k} C_j^{(r)\text{SUSY}}(M_{\text{SUSY}}), \quad (15)$$

where the magic numbers a_k , $b_k^{(i,j)}$ and $c_k^{(i,j)}$ are found in Ref. [18] and $\eta = \alpha_s(M_{\text{SUSY}})/\alpha_s(m_W)$. The off-diagonal element M_{12} obtained by $M_{12} = \langle B^0 | \mathcal{H}_{eff}^{\Delta B=2} | \bar{B}^0 \rangle / 2m_B$ consists of the bag parameters B_i and the decay constant f_{B_d} in vacuum insertion approximation.

IV. NUMERICAL RESULTS

We write $(\delta_{13})_{RL(RR)} \equiv |(\delta_{13})_{RL(RR)}|e^{i\varphi}$. Figure 1 shows the allowed values of the quantity \mathcal{S} as a function of the phase φ , assuming $(\delta_{13})_{RL}$ dominating case with $|(\delta_{13})_{RL}| = 0.001$. We vary the weak phase γ from 0 to 2π . Hereafter we use the input parameters as follows: $m_B = 5.3$ GeV, $m_t = 174.3$ GeV, $m_b = 4.6$ GeV, and $\alpha_s(m_Z) = 0.118$. The decay constant $f_{B_d} = 200 \pm 30$ MeV is the main source of the theoretical uncertainty and the bag parameters are those of Ref. [19] $B_1 = 0.87$, $B_2 = 0.82$, $B_3 = 1.02$. The supersymmetric scale is taken to be $m_{\tilde{g}} \approx \tilde{m} \approx M_{\text{SUSY}} \approx 500$ GeV. We require that the mass difference Δm_B and β_{mix} in $B \rightarrow J/\psi K$ decay should be within the experimental limit: $\Delta m_B = 0.489 \pm 0.008$ ps $^{-1}$ [20] and $\sin 2\beta_{\text{mix}} = 0.734 \pm 0.055$ [2]. On the other hand, it is reported that the branching ratio of the inclusive $B \rightarrow X_d \gamma$ decay puts a stringent constraint on the flavor mixing parameters of the gluino-squark contributions [17]. In spite of the recent measurement of the decay rate of the exclusive $B \rightarrow \rho/\omega \gamma$ channel, we do not use $\text{Br}(B \rightarrow \rho/\omega \gamma)$ as a constraint here since it involves a large theoretical uncertainty in the form factor. Instead, we assume a moderate upper bound $\text{Br}(B \rightarrow X_d \gamma) < 1.0 \times 10^{-5}$ in this analysis, following Ref. [17] and referring to the measurement of the exclusive channel [5], although no experimental limit on the branching ratio for the inclusive decay is given yet. In the figure, the black region corresponds to the allowed values for the phase of $(\delta_{13})_{RL}$, while the grey (green) region to the parameter sets which satisfy the Δm_B and $\sin 2\beta_{\text{mix}}$ constraints but exceeds the bound on the branching ratio of the inclusive $B \rightarrow X_d \gamma$ decay. We find that large CP violating asymmetry reaching $\sim \pm 60\%$, is possible while all other experimental constraints are satisfied. As we can notice from Eq. (10), the maximal value of the CP violating asymmetry is set by the coefficient $2|C_7||C'_7|/(|C_7|^2 + |C'_7|^2)$. In the present case, this coefficient is roughly 0.6 because the allowed value of $|C'_7|$ is about 0.1 for $|(\delta_{13})_{RL}| = 0.001$ (note $C_7 = C_7^{SM} = -0.31$ for $(\delta_{13})_{RL(RR)}$ dominating cases). If we increase the assumed value of $|(\delta_{13})_{RL}|$, the allowed range for the CP asymmetry, \mathcal{S} becomes expanded and may reach even $\pm 100\%$ if $|C_7| = |C'_7|$, which is realized when $|(\delta_{13})_{RL}| \sim 0.003$. However, such large $|C'_7|$ values would give large $B \rightarrow X_d \gamma$ branching ratio which exceeds the assumed upper limit of the branching ratio. Still the CP asymmetry $\mathcal{S} \sim \pm 0.8$ is allowed while satisfying experimental constraints including the inclusive branching ratio bound.

The plot for the allowed range of \mathcal{S} with respect to $|(\delta_{13})_{RL}|$ is depicted in Fig. 2 when the phase φ is fixed to be zero. The black region and the grey (green) region are defined as in Fig. 1. We see that the value of the CP asymmetry is zero for $|(\delta_{13})_{RL}| = 0$, which corresponds to the SM case with vanishing d -quark mass limit. As already explained, when $|(\delta_{13})_{RL}|$ value increase, the CP asymmetry \mathcal{S} increase and reach its maximal value at $|(\delta_{13})_{RL}| \sim 0.003$ and then decrease again. Here we notice two points. First, $|(\delta_{13})_{RL}|$ is strongly constrained by the inclusive branching ratio. In fact, the branching ratio bound is much stronger than the bounds on Δm_B and $\sin 2\beta_{\text{mix}}$. This is because $b \rightarrow d\gamma$ decay rate is very sensitive to $(\delta_{13})_{RL}$ mass insertion due to the enhancement factor $m_{\tilde{g}}/m_b$ as one can check it from Eq. (13). On the other hand, there is no such enhancement factor for the $B-\bar{B}$ mixing process. Second, a large CP violation (up to $\sim 35\%$) is still possible even when the only source of CP violating phase is the CKM mixing matrix, *i.e.*, when $C_7^{\text{eff}}(m_b)$ is real. The branching ratio $\text{Br}(B \rightarrow X_d\gamma)$ and CP asymmetry \mathcal{S} provide the complimentary information on $(\delta_{13})_{RL}$.

Figure 3 and 4 are the counterparts of Fig. 1 and 2 respectively, when $(\delta_{13})_{RR}$ dominates. The black region and the grey (green) region are defined as in Fig. 1 and 2. In Fig. 3, $|(\delta_{13})_{RR}| = 0.03$ is assumed while the phase φ is varied from 0 to 2π . We find that CP asymmetry \mathcal{S} reach $\sim \pm 5\%$ at best. This small CP asymmetry comes from the fact that $|C_7'|$ is small, compared to $|C_7|$. The CP asymmetry increases a little as we increase $|(\delta_{13})_{RR}|$. But we cannot increase $|(\delta_{13})_{RR}|$ enough to produce large CP asymmetries (say, larger than 10%). This is because the Δm_B and $\sin 2\beta_{\text{mix}}$ constraints are stronger than the branching ratio bounds in the $(\delta_{13})_{RR}$ dominating case. (Note that the opposite is true for the $(\delta_{13})_{RL}$ dominating case.) The phase φ is set to be zero in Fig. 4, while varying $|(\delta_{13})_{RR}|$. We can see that the CP asymmetry is so small that it might be difficult to measure it in the near future.

In short, large CP asymmetry is possible for the $(\delta_{13})_{RL}$ dominating case. On the other hand, only small CP asymmetry is allowed for the $(\delta_{13})_{RR}$ dominating case. The difference of these two cases is due to the enhancement factor $m_{\tilde{g}}/m_b$ in the case of $(\delta_{13})_{RL}$ mass insertion.

V. CONCLUDING REMARKS

If we observe a sizable CP asymmetry in $B^0 \rightarrow \rho^0\gamma$ decay, it will be a clear evidence of the new physics beyond the SM. Although it is hardly expected that the time dependent CP asymmetry of $B^0 \rightarrow \rho^0\gamma$ will be measured in the present B -factory, it will be achieved in the next generation of B -factory with about 100 times more B mesons produced. Due to the agreement of the SM prediction with the present Δm_B data and the CP asymmetry in $B \rightarrow J/\psi K$ decay, we favor the new physics which contributes less to the $B-\bar{B}$ mixing but has a strong effect on the $b \rightarrow d\gamma$ penguin diagram. In this paper, we showed that the RL mass insertion of squark mixing of the MSSM can produce a large CP asymmetry of $B^0 \rightarrow \rho^0\gamma$ decay process.

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- [1] G. Buchalla and A. J. Buras, Phys. Lett. B **333**, 221 (1994); Nucl. Phys. **B548**, 309 (1999).
 - [2] K. Abe *et al.*, Belle Collaboration, Phys. Rev. D **66**, 071102 (2002); A. Aubert *et al.*, BaBar Collaboration, Phys. Rev. Lett. **89**, 201802 (2002).
 - [3] B. Dutta, C. S. Kim and S. Oh, Phys. Rev. Lett. **90**, 011801 (2003); B. Dutta, C. S. Kim, S. Oh and G. H. Zhu, arXiv:hep-ph/0312389; S. Khalil and E. Kou, Phys. Rev. D **67**, 055009 (2003); J.-P. Lee and K. Y. Lee, Euro. Phys. J. C **29**, 373 (2003); G. L. Kane *et al.*, Phys. Rev. Lett. **90**, 141803 (2003); V. Barger *et al.*, Phys. Lett. B **580**, 186 (2004).
 - [4] C. S. Kim, T. Morozumi and A. I. Sanda, Phys. Rev. D **56**, 7240 (1997); D. Atwood, B. Blok and A. Soni, Int. J. Mod. Phys. A **11**, 3743 (1996); Nuovo Cimento **109A**, 873 (1996).
 - [5] M. Iwasaki (Belle Collaboration), Talk presented at the XXIXth Rencontres de Moriond Electroweak Interactions and Unified Theories, La Thuille, Aosta Valley, Italy, March 21–28, 2004.
 - [6] A. Ali and L. T. Handoko, and D. London, Phys. Rev. D **63**, 014014 (2000).
 - [7] A. Ali and E. Lunghi, Euro. Phys. J. C **26**, 195 (2002).
 - [8] K. Kiers, A. Soni and G.-H. Wu, Phys. Rev. D **62**, 116004 (2000).
 - [9] A. Ali and V. M. Braun, Phys. Lett. B **359**, 223 (1995).
 - [10] A. Khodjamirian, G. Stoll, and D. Wyler, Phys. Lett. B **358**, 129 (1995).
 - [11] D. Atwood, M. Gronau and A. Soni, Phys. Rev. Lett. **79**, 185 (1997).
 - [12] A. Ali, V. M. Braun, H. Simma, Z. Phys. C **63**, 437 (1994).
 - [13] L. Everett *et al.*, JHEP **0201**, 022 (2002).
 - [14] S. Baek *et al.*, Nucl. Phys. **B609**, 442 (2001).
 - [15] A. J. Buras *et al.*, Nucl. Phys. **B566**, 3 (2000); T. Besmer, C. Greub, and T. Hurth, Nucl. Phys. **B609**, 359 (2001).
 - [16] F. Gabbiani *et al.*, Nucl. Phys. **B477**, 321 (1996).
 - [17] P. Ko, G. Kramer, and J.-h. Park, Euro. Phys. J. C **25**, 615 (2002).
 - [18] D. Becirevic *et al.*, Nucl. Phys. **B634**, 105 (2002).
 - [19] D. Becirevic *et al.*, JHEP **0204**, 025 (2002).
 - [20] K. Hagiwara *et al.*, *Review of Particle Physics*, Phys. Rev. D **66**, 010001 (2002).

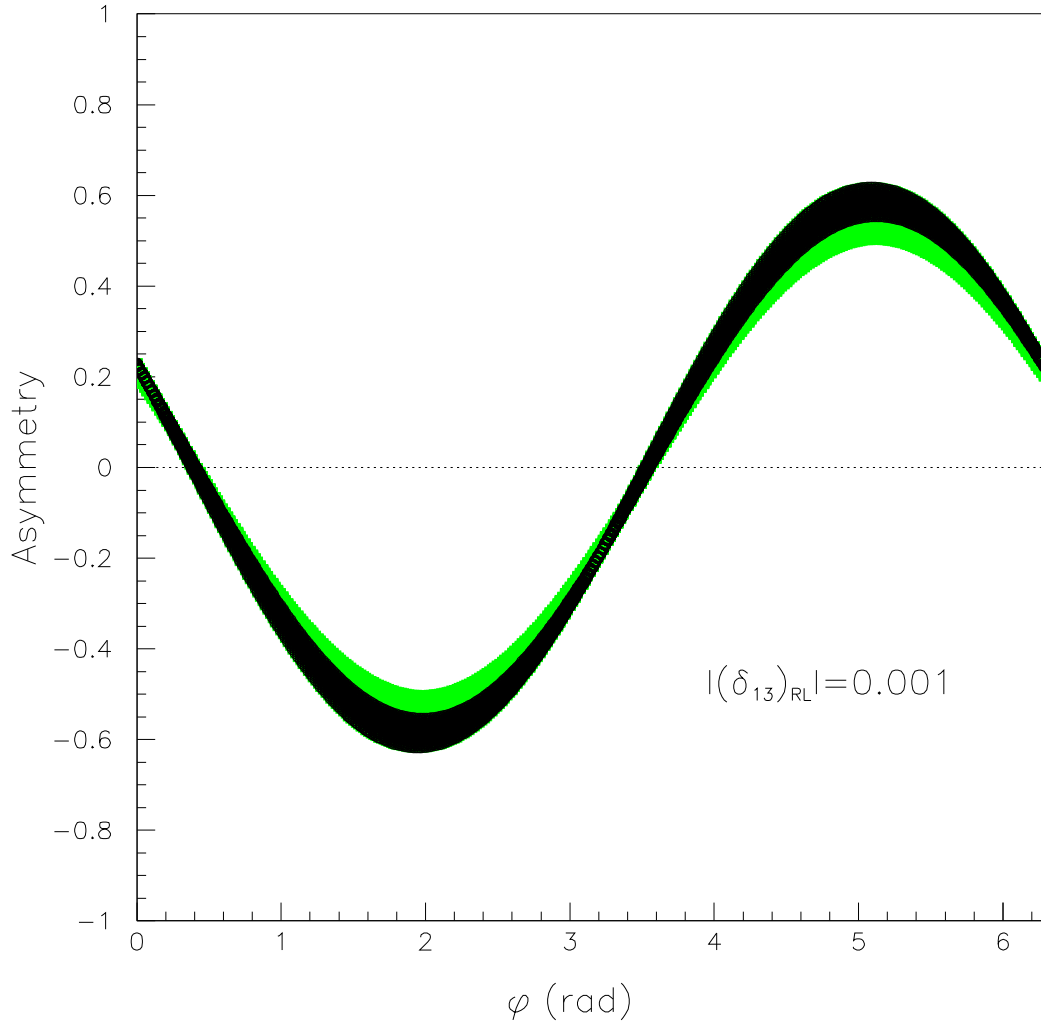


FIG. 1: The time-dependent CP asymmetry \mathcal{S} as a function of the phase of $(\delta_{13})_{RL}$. $|(\delta_{13})_{RL}| = 0.001$ is assumed. The black region denotes allowed points while grey (green) region excluded points by the inclusive $b \rightarrow d\gamma$ branching ratio bound.

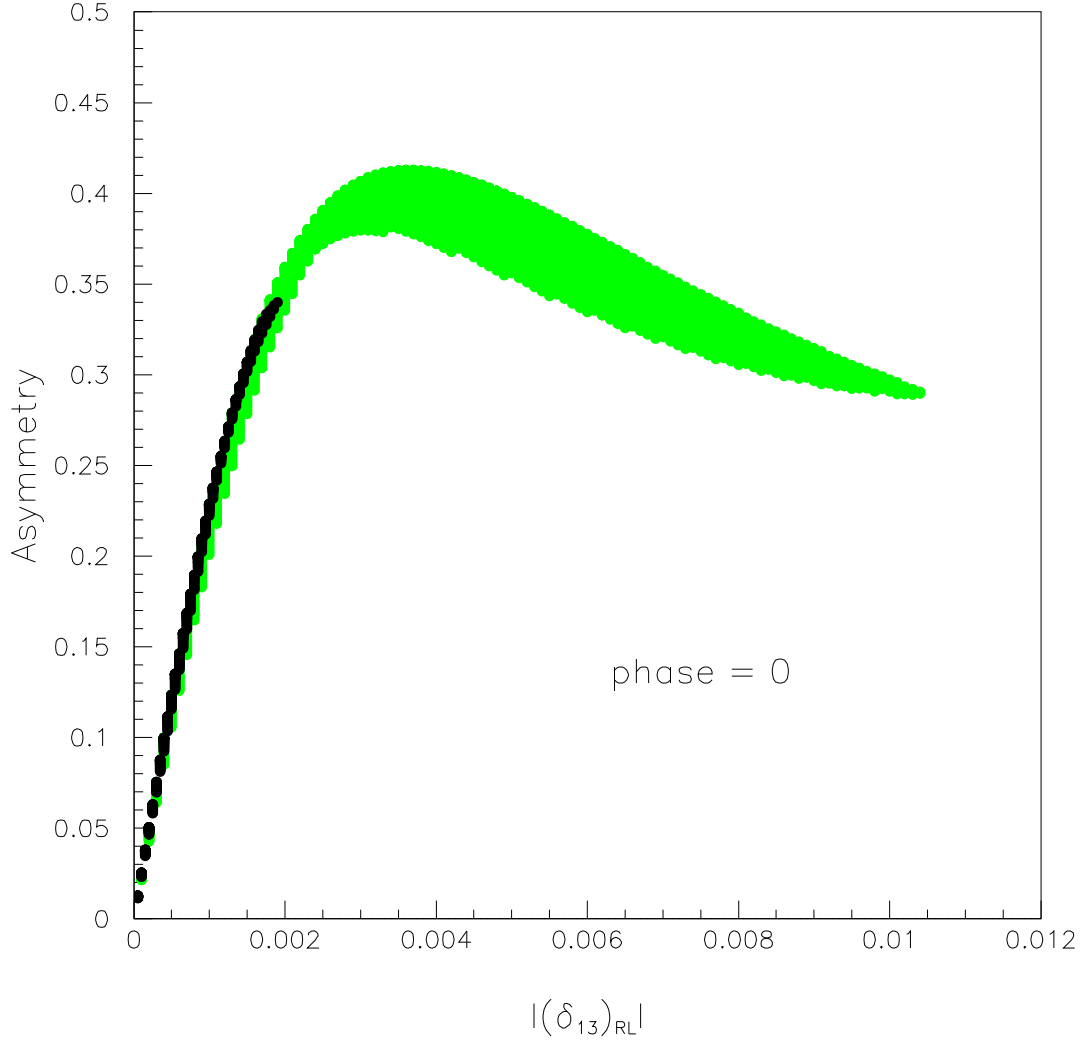


FIG. 2: The time-dependent CP asymmetry \mathcal{S} as a function of $|(\delta_{13})_{RL}|$. The phase of $(\delta_{13})_{RL}$ is assumed to be 0. The black region denotes allowed points while grey (green) region excluded points by the inclusive $b \rightarrow d\gamma$ branching ratio bound.

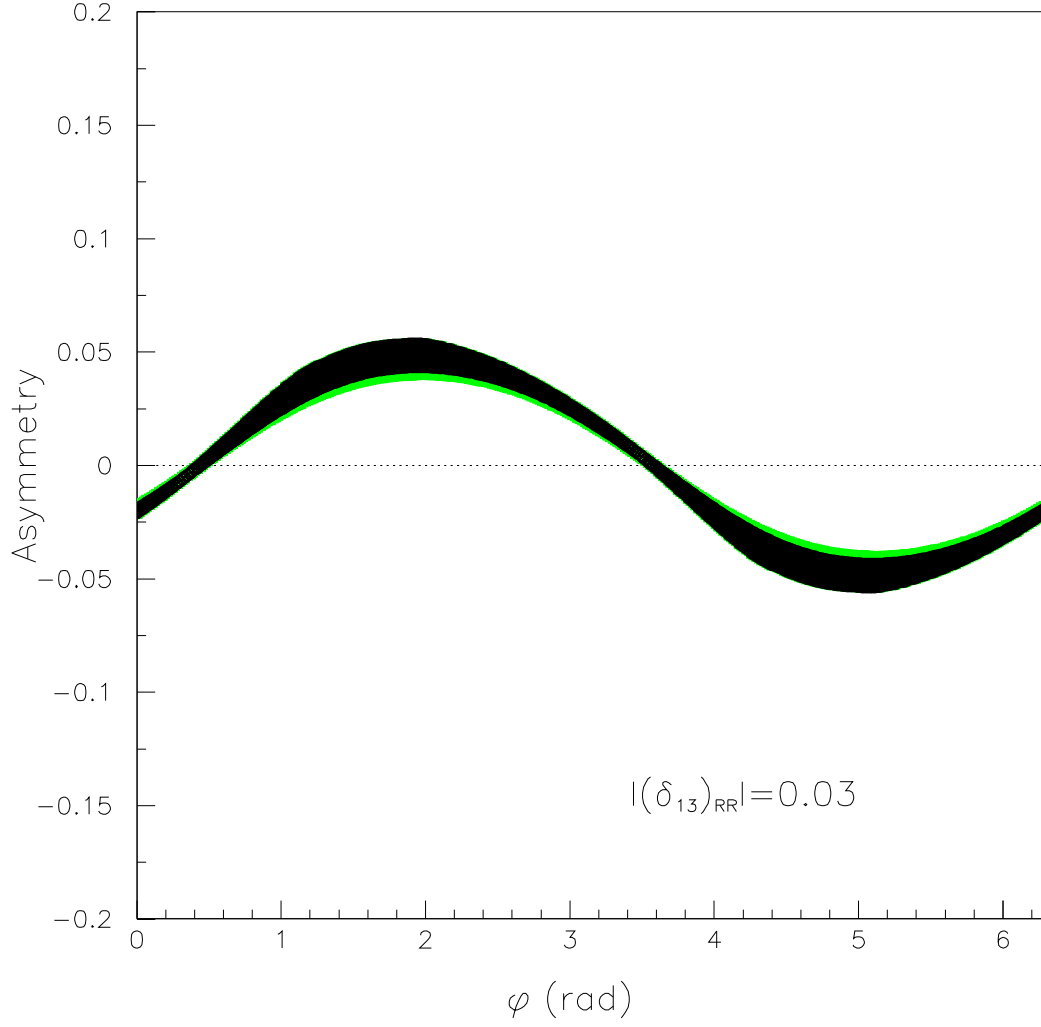


FIG. 3: The time-dependent CP asymmetry \mathcal{S} as a function of the phase of $(\delta_{13})_{RR}$. $|(\delta_{13})_{RR}| = 0.03$ is assumed. The black region denotes allowed points while grey (green) region excluded points by the inclusive $b \rightarrow d\gamma$ branching ratio bound.

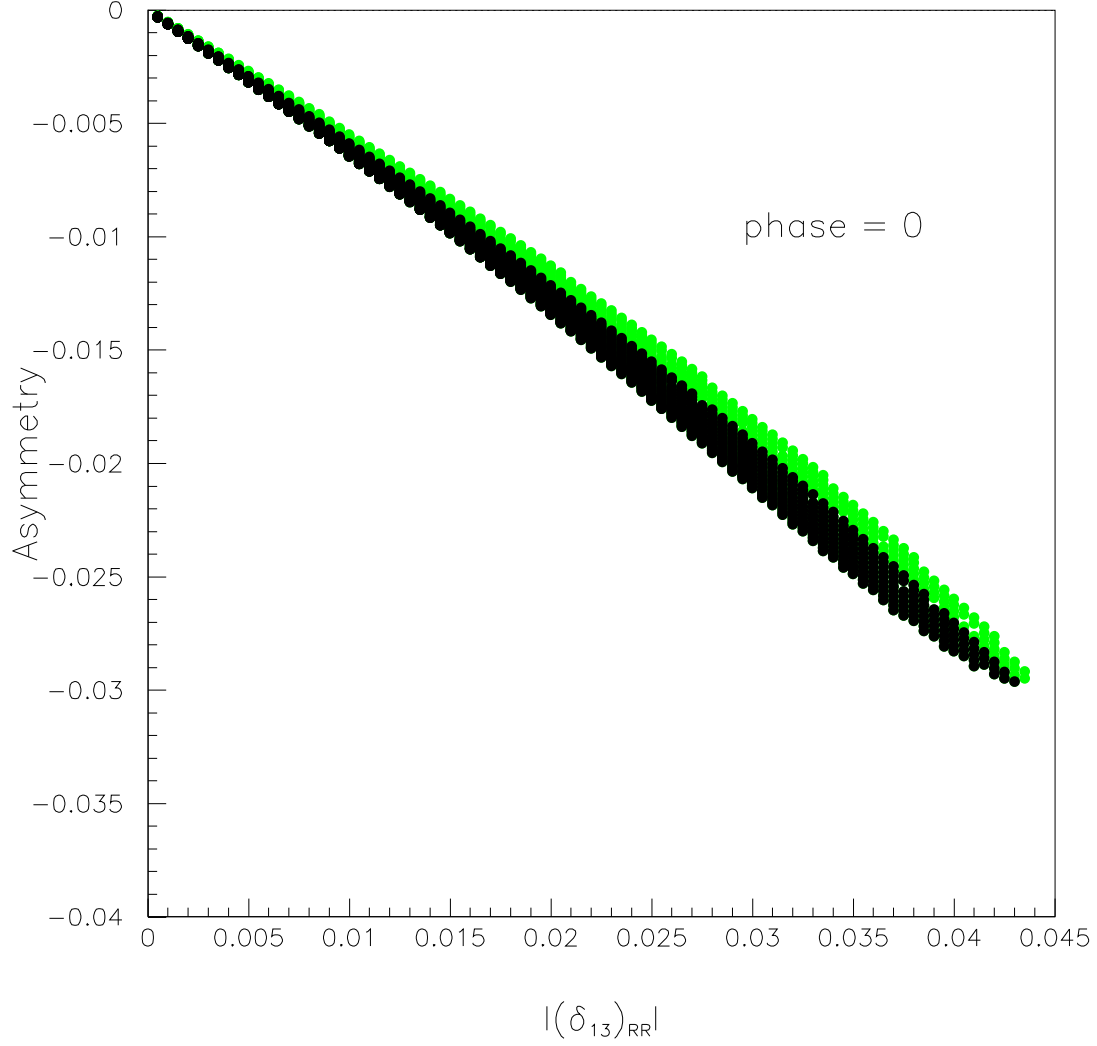


FIG. 4: The time-dependent CP asymmetry \mathcal{S} as a function of $|(\delta_{13})_{RR}|$. The phase of $(\delta_{13})_{RR}$ is assumed to be 0. The black region denotes allowed points while grey (green) region excluded points by the inclusive $b \rightarrow d\gamma$ branching ratio bound.